Analog and Digital Electronics for Mechatronics
Design: Switch
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0.Problem Statement and Analysis:

Speed control of a DC brushed gear motor,

1.The motor may draw from 250 mA of current when no mechanical load, to 10A current when at its maximum torque and stall speed. On the average, it draws 1.58A of current when operated near its most efficient speed.
It is a 12V motor, meaning it can be supplied with any voltage from 0V to 12V without damage.
2.Pulse-width modulation to control the speed motor,
circuit will operate the motor either fully ON (supply close to 12V to the motor) or fully OFF (supply 0V to motor). By switching between these two states very rapidly (at f>>motor speed), and by varying the relative amount of time spent in the ON state relative to the OFF state per cycle, you can achieve speed control with high efficiency.

3.1 The circuit is powered by high-current voltage supply VDD. The value of VDD will be selected later, while it satisfies the constraint that "the voltage across the motor is less than 12V" at any time.
3.2 The speed control input to this circuit has two states, representing when the motor should be 'ON' and 'OFF'. The 'ON' state is taken when V_{speed}=3.3V and in the 'ON' state, the circuit should apply 12V across the motor terminals.
Similarly, the 'OFF' state could happen when V_{speed}=0V, in which case the circuit should deliver 0V to the motor as well. However, if it is beneficial to your design, you may reverse the values of which relate to 'ON' and 'OFF' (that is, you are allowed to instead select V_{speed}=0V → motor ON and V_{speed}=3.3V → motor OFF) Very little or no current (<10mA) should flow into this input.

3.3 Since the motor voltage is zero in the 'OFF' state, your circuit is naturally efficient in this state (no power is drawn by the load). However, in the 'ON' state, you should select your components such that the efficiency of your circuit is at least 95%. That is, you have a single supply voltage VDD, that powers the motor and your circuit. If the motor and circuit together draw Itotal current, then the total power used by the motor and circuit together is Ptotal=ItotalVDD. Similarly, the power used by the motor alone is Pmotot=VmotorImotor. Note that Vmotor should be close to 12V when the circuit is in the 'ON' state. Efficiency is the fraction of total power delivered to the load (the motor):
Efficiency=η=Pmotor/Ptotal

3.4 Be careful not to confuse the efficiency of your circuit with the motor's efficiency (listed in the provided link). The motor's efficiency refers to the conversion of electrical energy into mechanical motion, and is not used in any calculations in this assignment.

3.5 All components should be selected to take into account real-world limits.That is, the circuit should be designed to not have any device exceed its maximum ratings for power, current, or voltage. To keep costs and complexity limited, the circuit should not use any op-amps or specialized integrated circuits – only MOSFETs and passive components are needed.

1.Engineering Specification of to-be-designed system:

- **Speed Control Input of the circuit system**: V_{speed}=3.3V for motor state 'ON' or V_{speed}=0V for motor state 'OFF'. (or reversed), while current flowing into this input is less than 10mA.
- **High-current Input of the circuit system (voltage supply of the circuit)**: V_{DD}, the value of V_{DD} will be discussed later, while it satisfies the constraint that "the voltage across the motor is less than 12V" at any time. (the circuit implies that V_{DD} is at least 12V)
- **Output of the circuit system**: circuit will operate the motor either fully ON (supply close to 12V to the motor) or fully OFF (supply 0V to motor), while the output current is no more than 10A and no less than 250mA.
- **Efficiency of the system**: more than 95%
- **Components of the system**: all components are selected according to real-world limits, only consists of MOSFETs and passive components, no Op-Amps or IC used.

2.Block diagram of Conceptual Design Solution:

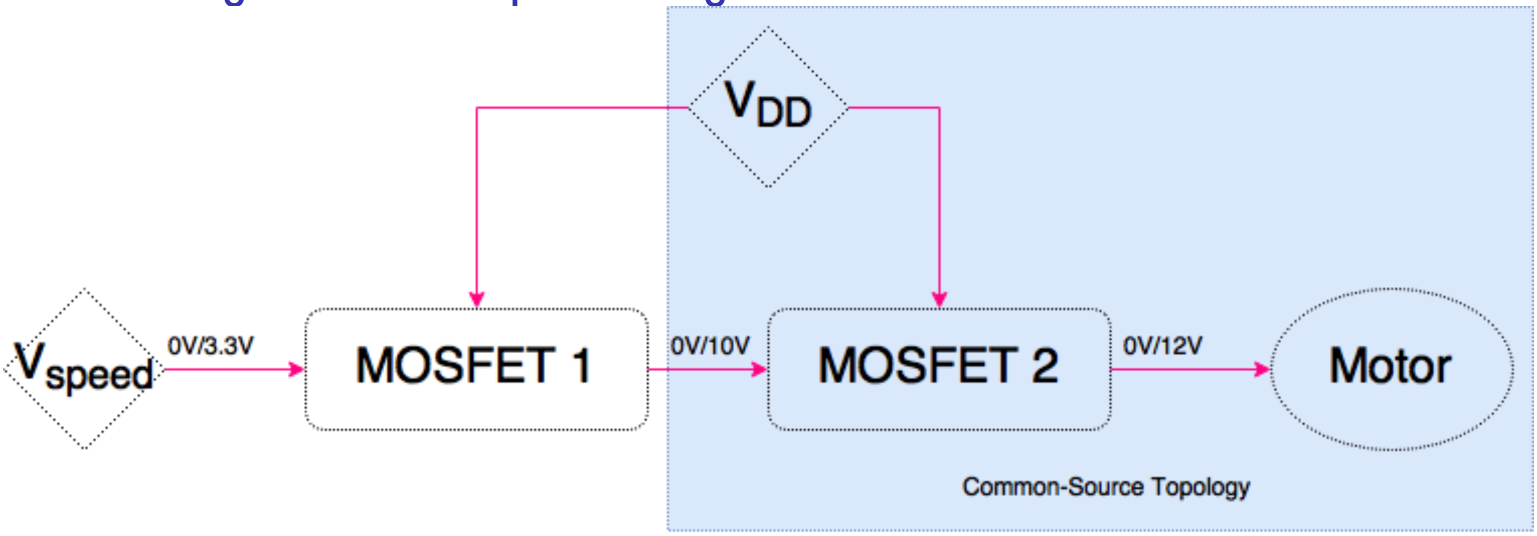

Figure · Block Diagram for planned circuit

3&4&5.Design of MOSFET 2:

Selection of circuit topology: common-source topology
Selection of MOSFET: SiR494DP

When the motor is powered at free mechanical load with 250mA, the analytical power consumed by the motor is P_{motor}=250mA×12V=3W. Whereas at full load, power consumed by the motor is P_{motor}=10A×12V=120W. At its most efficient speed, it draws 1.58A current with 18.96W. If the desired efficiency of circuit is more than 95%, the controlling circuit (MOSFET2 & MOSFET1) should dissipate less than (3W/95%)-3W=0.158W, if no loading at the motor.

Desired:
control input as 0V/10V, voltage supply V_{DD}(TBD), voltage across the motor 0V/12V(maybe less than 12V) with current 250mA≤I≤10A, circuit efficiency more than 95%.

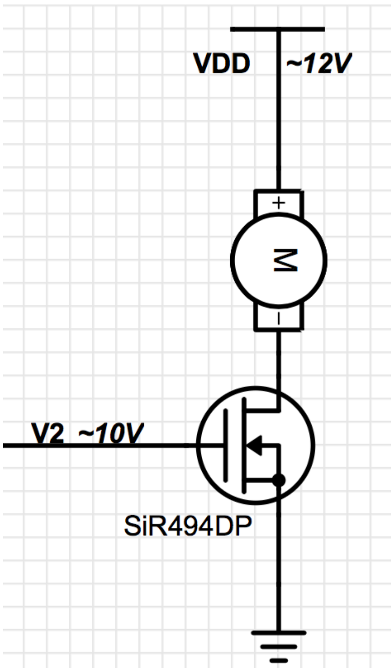

Figure · Circuit Diagram for MOSFET 2

※ Verification:

①Efficiency of circuit:

If the MOSFET is in cut-off mode, knowing that $I_D=I_{load}=0$, so the motor 'OFF' state can be achieved. For motor 'ON' state, assume the MOSFET is in triode mode, where the MOSFET can be replaced by a resistor with resistance R_{DSON}.

For MOSFET SiR494DP , $R_{DS(on)}=0.0012\Omega$ at $V_{GS}=10V$.

Suppose the motor is operating at 1.58A load at 12V.
with $V_S=0V$, $V_D=V_S+R_{DSON}\times I_D=0+(0.0012\Omega)\times 1.58A = 1.896\times 10^{-3}V$
$P_{MOSFET}=(V_D-V_S)\times I_D=(1.896\times 10^{-3}V-0V)\times(1.58A)=2.99568\times 10^{-3}W$
V_{DD} is selected to be $12V+1.896\times 10^{-3}V.=12.001896V\approx 12V$
$P_{motor}= 12V\times 1.58A=18.96W$
efficiency $\eta=P_{motor}/P_{total}= (18.96W)/(18.96W+2.99568\times 10^{-3}W)\times 100\%=99.9842\%$ at motor most efficient mode.

Check the free load mode and full load mode:
At free load, $P_{total}=12.001896V\times 250mA=3.000474W$ while $P_{MOSFET}=0.0012\Omega\times 250mA=0.0003W$,
so $\eta=(P_{total}-P_{MOSFET})/P_{total}=99.99\%$
At full load, $P_{total}=12.001896V\times 10A=120.01896W$ while $P_{MOSFET}=0.0012\Omega\times 10A=0.012W$,
so $\eta=(P_{total}-P_{MOSFET})/P_{total}=99.99\%$

Then, check the maximum ratings of the MOSFET of the circuit.
②Functionality of circuit:
- **Power**: maximum power dissipation at T=25°C is $P_D=104W$ and at T=70°C is $P_D=66.6W$, which exceeds the power we expect to dissipate in this application, and thus we are within the provided rating.
- **Current**: continuous drain currents are 60A at 25°C or 70°C, which exceeds the maximum load current 10A.
- **Voltage**: in the 'ON' state, where the MOSFET is in triode mode, V_{DS} at 250mA load is $0.0012\Omega\times 250mA=3\times 10^{-4}V$, and at full load 10A, $V_{DS}=0.0012\Omega\times 10A=0.012V$. While the drain-source voltage is 12V, the safety margin of drain-to-source voltage is more than (12V-0.012V)/12V=99.9%; thus a diode parallel to motor to restrict the inductive spikes is not necessary.
- Also, gate-source voltage is ±20V, which is more than 10V, which will be applied to gate of MOSFET.

③A diode will not be added to be parallel to the motor to restrict inductive spikes.

6&7. Design of MOSFET 1: (MOSFET for level shifting)

Selection of circuit topology: common-source topology
Selection of MOSFET: CSD23285F5 with Threshold Voltage -0.95V

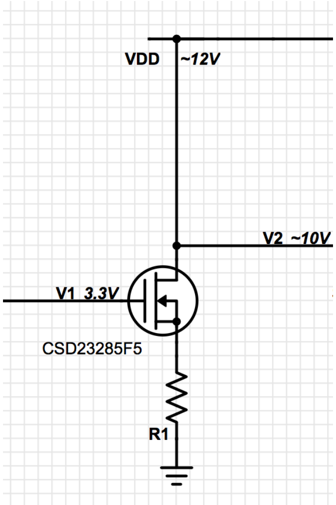

Figure · Circuit Diagram for MOSFET 1

※ Verification:
a)Functionality of circuit:
To be designed, gate voltage $V_G=3.3V$.
While the maximum VDS for MOSFET is -12V.

The output V2 is supposed to be around 10V, so V_{GS} is around 3.3-10V=-6.7V. (less than threshold voltage, good!) At V_{GS}=–4.5 V, Drain-to-Source On-Resistance $R_{DS(ON)}$=29mΩ. When V_{GS}=-6.7V, RDS(on) will be less than 29mΩ.

Continuous drain current is –5.4A, and maximum power dissipation is 1.4W. At $R_{DS(ON)}$=29mΩ, if the circuit is powered by V_{DD}=12.001896V, the current at drain is I_D=413.85A, which is dramatically larger than its current limit. So a resistor will be added to the circuit to limit the total drain current. R≥12.001896V/5.4A=2.2225Ω. While the value of R should be limited, in order to satisfy the efficiency requirements. (its value will be settled later)

With $R_{DS(ON)}$ around 29mΩ and current less than -5.4A, the power dissipation is less than 0.845W, which is less than maximum power dissipation P_D=1.4W.

b)Efficiency of circuit: efficiency of this circuit depends on the choice of R, which will be discussed in the complete schematics in part 8 later.

8. Schematic of Circuit:

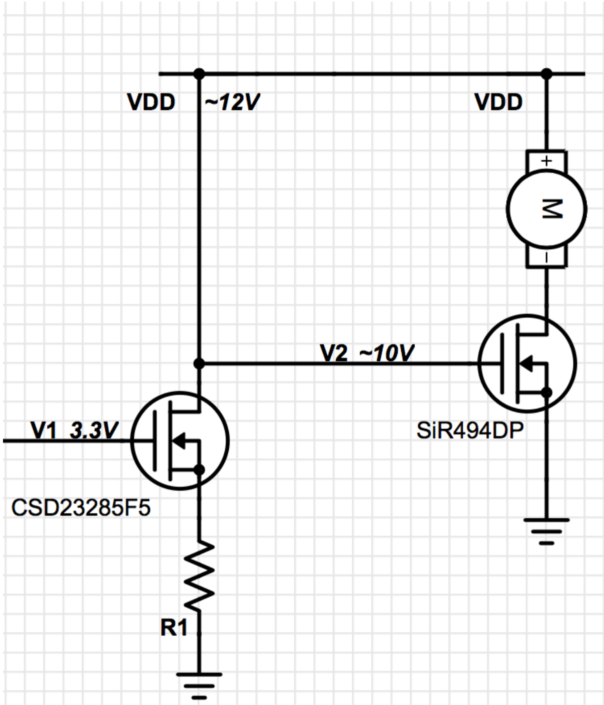

Figure · Schematic of Entire Circuit

※ Verification:
a) Efficiency of entire circuit:
For MOSFET 2 (SiR494DP), $R_{DS(on)}$=1.2mΩ, and for MOSFET 1 (CSD19531KCS), $R_{DS(on)}$=7.3mΩ.
R≥12.001896V/78A=0.15387Ω.
The minimum power dissipation of motor is at free load with 250mA, P_{motor}=12V×250mA=3W. So the entire circuit power should be less than 3W/95%=3.15789W in order to meet the efficiency requirement.
The resistor should be more than 12V*12V/(3.15789W-3W)=912Ω. Select 1kΩ for safety margin.

b) Functionality of entire circuit:
The threshold voltage of MOSFET1 is -0.65V., while $R_{DS(ON)}$ is less than 29mΩ, and R1 is 1kΩ, V2 would be around 12V, so VGS is around -8.7V makes MOSFET1 in triode mode and V2 is more than 10V which exceeds the threshold of MOSFET2, which leads to MOSFET2 in triode mode and the motor is powered on.

Component	Selected	Manufacturer	Number × Cost	Data Sheet
MOSFET 2	SiR494DP	Vishay Siliconix	1 × 1.135	http://www.vishay.com/docs/64824/sir494dp.pdf
MOSFET 1	CSD23285F5	Texas Instruments	1 × 0.31100	http://www.ti.com/lit/ds/symlink/csd23381f4.pdf
Protection Diode	NA	NA	NA	NA
Protection Resistor	CF14JT1K00TR-ND	Stackpole Electronics Inc.	1 × 0.00718	https://www.seielect.com/Catalog/SEI-CF_CFM.pdf

Table · Components Breakdown

Improvements of design:
In fact, the threshold voltage of MOSFET 2 is 2.5V. Directly applying 3.3V on the gate of it can make it as a switch. MOSFET 1 is redundant.

Reference

DC brushed gear motor: http://www.robotshop.com/ca/en/lynxmotion-12v-90-rpm-9911oz-in-1269-brushed-dc-gear-motor-w--encoder.html